

CANDLE FLAMES IN MICROGRAVITY

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Introduction

This work is a study of a candle flame in a microgravity environment. The purpose of the work is to determine if a steady (or quasi-steady) flame can exist in a microgravity environment, study the characteristics of the steady flame, investigate the pre-extinction flame oscillations observed in a previous experiment in more detail, and finally, determine the nature of the interactions between two closely spaced candle flames. The candle flame is used as a model combustion system, in that in microgravity it is one of the only examples of a non-propagating, steady-state, pure diffusion flame. Others have used the candle to study a number of combustion phenomena including flame flicker¹, flame oscillations²⁻⁴, electric field effects⁵ and enhanced⁶ and reduced⁷ gravitational effects in flames.

The present work is a continuation of a small-scale Shuttle experiment on candle flames^{8,9}. That study showed that the candle flame lifetimes were on the order of 40 seconds, the flames were dim blue after a transient ignition period, and that just prior to extinction the flames oscillated spontaneously for about five seconds at a frequency of 1 Hz. The authors postulated that the gas phase in the immediate vicinity of the flame was quasi-steady. Further away from the flame, however, the assertion of a quasi-steady flame was less certain, thus the authors did not prove that a steady flame could exist. They also speculated that the short lifetime of the candle flame was due to the presence of the small, weakly perforated box that surrounded the candle.

The Candle Flames in Microgravity (CFM) experiment, with revised hardware, was recently flown aboard the Mir orbiting station, and conducted inside the glovebox facility by Dr. Shannon Lucid. In addition to the purposes described above, the experiments were NASA's first ability to ascertain the merits of the Mir environment for combustion science studies. In this article, we present the results of that experiment. We are also in the process of developing a numerical model of the microgravity candle flame. The status and results of the modeling efforts to date are also presented.

Experimental Apparatus

The design of the experiment is based on the USML-1 CFM experiment described elsewhere^{8,9}. The experiments are conducted inside a glovebox facility that provided power, video and photographic capabilities and provided a level of containment. The main module of the experiment was a 20 cm cube-shaped wire mesh screen as opposed to the 12.5 cm perforated Lexan box used on USML-1. More importantly, the screen provided more than 50% free area (as opposed to less than 15% on USML-1) yielding less resistance for oxygen to diffuse to the flame and combustion products to diffuse away from the flame. The ignition system was a coiled 250 μ m aluminum alloy wire heated with a current of approximately 3 amperes. For all of the experiments, the igniter was on for a preset time of 4 or 5 seconds. This was sufficient to ignite the candle in almost all of the tests.

On USML-1, 7 identical candles (2.5 mm wick diameter, 5 mm candle diameter, 12 mm candle length, and 3 mm initial exposed wick length) were tested. In the Mir experiments, a variety of candle types were flown. There were 79 total candles supplied with the hardware with three different wick diameters (approximately 1, 2 and 3 mm), two different candle diameters (5 and 10 mm) and two different lengths of initially exposed wick (3 and 6 mm). All candles were 2 cm in length.

The glovebox facility is in the Priroda module of the Mir orbiting station. All of the candles were burned over an approximately 3 week period. The Mir operates at nominally atmospheric pressure with an oxygen concentration that is higher than air. For the candle tests, the oxygen mole fraction in the ambient was between 0.22 and 0.25. The value is that measured and down-linked by the Russian oxygen sensors and pressure transducers on-board Mir. The Russian cosmonauts calibrate the oxygen sensor every two weeks as a regular maintenance procedure.

The data consisted of video and still photography, crew audio commentary, thermocouple measurements, and radiometric measurements and a single point oxygen measurement. The radiometer and oxygen sensor were interchangeable and located approximately 10 cm from the tip of the flame. The primary purpose of the oxygen sensor was to ensure that the ambient oxygen concentration was below 30% (safety mandate). We also hoped to determine the oxygen concentration at the sensor location (10 cm from the candle wick) as the candle burned. The still photographs were from a 35 mm SLR camera with ASA 200 film. A higher speed film would have been better, but could not be used because of anticipated film-fogging problems from prolonged exposure to cosmic radiation. The pictures indeed show a small degree of fogging due to radiation. The camera's shutter remained open until sufficient light was collected, based on central-spot metering of the candle flame; often this meant that the pictures were integrated averages of the behavior of the candle flame over 10 second intervals. The flames were too faint for the glovebox-supplied video cameras to record the flame shape when it was entirely blue.

Experimental Observations

Qualitatively, all of the candles burned similarly in the following ways. Immediately after ignition, the flames were very luminous and hemispherical, resembling the flames on USML-1. The yellow luminosity, presumably from soot, lasted well into the flame lifetime, however, unlike on USML-1. As the burning progressed, heat feedback from the flame rapidly melted the wax. For the 5 mm diameter candles, all of the exposed wax melted within 2 minutes of ignition. The shape of the candle and wax then looked as in Figure 1(b). After some time, this molten ball of wax became unstable and 'collapsed' suddenly as it moved back along the candle holder as shown in Figure 1(c). After the collapse, the yellow luminosity disappeared and the flame became dim blue, similar to the USML-1 candle flames. The flames then remained dim blue until extinction.

All of the candles burned substantially longer than the longest candle flame lifetime on USML-1. The Mir experimental flame lifetimes varied from slightly over 100 seconds to over 45 minutes. The candles with the largest wicks had the shortest flame lifetimes and the candles with the smallest wicks had the largest flame lifetimes. The actual flame lifetime for seemingly identical candles varied significantly in some cases. The pre-extinction flame oscillations observed on USML-1 also occurred with the Mir flames. The oscillations also correlated with the type of wick. Specifically, no oscillations occurred in any of the experiments with the smallest wick diameter. Oscillations did occur in the other two wick diameters. The flames oscillated at a frequency similar to that on USML-1 only for a much longer time, for as long as 90 seconds in some cases. Also, although the flames on the smallest wicks did not *spontaneously* oscillate near extinction, they did oscillate when a thermocouple (and tube supporting the thermocouples) was moved close to the flame. The oscillations stopped immediately after the thermocouple was moved away from the flame.

Analysis of the 35 mm photographs yielded both the flame diameter, D , and flame height, H (both shown in Figure 1(a)) as functions of time. Additionally, the ratio H/D was also determined. The latter quantity yielded consistent behavior in the USML-1 candle tests⁹. For the USML-1 tests, H/D was initially 0.9 and decreased to approximately 0.7 at extinction (just before the oscillations). Figure 2 shows H , D , and H/D as a function of time for a Mir candle flame with a relatively long lifetime. The flame size increases for the first 75 sec of the flame lifetime, after which the flame size remains relatively constant (D remains constant, but H decreases slowly). This change in behavior at 75 seconds corresponds to the time of the collapse of the liquid wax. H/D is nearly steady until the collapse occurs after which it continuously decreases until extinction.

In general, the results (that have been analyzed to date) show that the flames were more reproducible than on USML-1. The flames typically increased in size initially and then remained at constant size or increased in size slowly as a function of time. H/D either decreased or remained constant as a function of time. The values of the flame size are consistent with USML-1, although the value of H/D is somewhat higher than on USML-1. This later observation could be due to the increased ambient oxygen concentration in the Mir tests. Our data reduction efforts are still underway. We do not yet report on the radiometric data nor the local oxygen sensor data because the former has not yet been examined in detail and the latter lacked sufficient resolution to draw satisfactory conclusions.

The purpose of using different wick sizes was to change the flame size. Figure 3 shows the flame diameter (D) as a function of time for the three different wick sizes. As expected, the larger the wick size, the larger the quasi-steady flame size. The mass burning rate of the candle flame should also be a function of the candle wick diameter. The three different wick sizes give burning rates that varied from 0.9 to 1.4 mg/s in normal gravity. The reduced gravity burning rates (based on the candle mass before and after the experiments) varied from approximately 0.2 mg/s for the smallest wick sizes to approximately 0.6 mg/s for the largest wick size.

During several of the tests, the lights were on and the glovebox cameras recorded the behavior of the liquid wax. As mentioned before, the liquid wax fully melted within 2 minutes of ignition. During and after melting, there was very significant motion in the liquid phase. The motion was apparent from seeing small bubbles that initiated near the wick. These bubbles were drawn towards the tip of the candle where they moved close to the surface and then moved quickly back towards the candle holder. This motion is consistent with surface-tension-driven flow that originates because of the lower temperature liquid that is present near the candle holder relative to that liquid closer to the flame.

One surprise was the amount of wax vapor that rapidly condensed into an aerosol that moved away from the candle flame. With the lights on, it could be seen that there was a significant amount of aerosol produced at the base of the flame near the candle holder. Throughout the lifetime of the flame, aerosol streamed out from the base of the candle and formed a ring around the inside of the candle box. This last observation was not evident on the video camera, but described in detail by the crew. The aerosol is in all likelihood condensed paraffin that is produced from the flame vaporizing the wax, and then moves along the candle (perhaps carried in the boundary layer produced by the liquid wax flow) and condenses as gets far enough away from the flame. After flame extinction, there was also a large, spherical vapor cloud that surrounds the candle and is centered at the wick.

Theoretical Model

We divide the modeling of the candle flame into two tasks. The first part treats in detail the gas phase, but with a simplified liquid phase. This is presented below. The second part will treat the liquid phase in more detail, considering the wick as a porous media through the liquid wax flows. This second phase will be completed and coupled with the gas-phase treatment in the future.

The gas-phase model assumes that the fuel is evaporated from a small porous sphere maintained at a constant radius, R , that is coated with liquid fuel. This sphere is connected to a thin rod with a prescribed temperature distribution. This thin rod is inert and acts as a heat sink to simulate the flame quenching aspect of the candle wick. Figure 1(a) shows a schematic of the problem.

Assuming axisymmetry, the mathematical formulation utilizes a two-dimensional spherical coordinate system also shown in Figure 1(a). The model assumes: one-step second-order overall Arrhenius reaction, constant specific heats and thermal conductivity, constant Lewis number for each species (although different species can have different, constant Lewis numbers), ideal gas behavior and no buoyant force. The last assumption allows us to adopt a simplified treatment of the momentum equation¹⁰. This includes the assumption of potential flow and the product $(\bar{\rho} \bar{T})$ to be constant. In addition, flame radiative losses from CO_2 and H_2O are present but a gray gas treatment is used. Finally, the liquid fuel is prescribed to be at the boiling point, T_b . The following non-dimensional variables are defined as (bars indicate dimensional quantities):

$$T = \frac{\bar{T} \bar{C}_p}{\bar{q}}; \quad r = \frac{\bar{r}}{R}; \quad \rho = \frac{\bar{\rho}}{\bar{\rho}_\infty}; \quad t = \frac{\bar{t} \bar{D}_\infty}{R^2}; \quad u_r = \frac{\bar{R} \bar{u}_r}{\bar{D}_\infty}; \quad u_\theta = \frac{\bar{R} \bar{u}_\theta}{\bar{D}_\infty}; \quad \phi = \frac{\bar{\phi}}{\bar{D}_\infty}; \quad \Phi = \frac{\bar{\Phi}}{\bar{D}_\infty}; \quad \omega_F = \frac{\bar{C}_p \bar{R}^2}{\bar{\lambda}} \bar{\omega}_F; \quad L = \frac{\bar{L}}{\bar{q}};$$

$$E = \frac{\bar{E} \bar{C}_p}{\bar{R} \bar{u}_r}; \quad Da = \frac{\bar{\rho}_\infty^2 \bar{C}_p \bar{R}^2}{\bar{\lambda}} \bar{A}; \quad q_r = \frac{\bar{R}^2 \bar{C}_p}{\bar{\lambda} \bar{q}} \bar{q}_r.$$

The non-dimensional equations are:

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \frac{\partial \Phi}{\partial r}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\frac{\sin \theta}{r} (\frac{\partial \Phi}{\partial \theta})) = \frac{\omega_F + q_r}{T_\infty}$$

$$\rho \frac{\partial Y_i}{\partial t} + \rho u_r \frac{\partial Y_i}{\partial r} + \frac{\rho u_\theta}{r} \frac{\partial Y_i}{\partial \theta} - \frac{1}{Le_i r^2} \frac{\partial}{\partial r} (r^2 (\frac{\partial Y_i}{\partial r})) - \frac{1}{Le_i r \sin \theta} \frac{\partial}{\partial \theta} (\frac{\sin \theta}{r} (\frac{\partial Y_i}{\partial \theta})) = v_i \omega_F$$

$$\rho \frac{\partial T}{\partial t} + \rho u_r \frac{\partial T}{\partial r} + \frac{\rho u_\theta}{r} \frac{\partial T}{\partial \theta} - \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \frac{\partial T}{\partial r}) - \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\frac{\sin \theta}{r} (\frac{\partial T}{\partial \theta})) = \omega_F + q_r$$

$$\omega_F = Da \rho^2 Y_o Y_F \exp(-\frac{E}{T})$$

where Φ is a coupling variable given by $\Phi = \phi - \frac{T}{T_\infty}$ and ϕ is the velocity potential. The boundary conditions are:

$$\begin{aligned}
& @ \quad r=1 \\
& \quad T = T_b \\
& \quad -\partial Y_F / \partial r = \rho u_r (1 - Y_F) \\
& \quad \partial Y_i / \partial r = \rho u_r Y_i \quad (i = O_2, CO_2, H_2O) \\
& \quad \partial \Phi / \partial r = (1/\rho L - 1/T_\infty) * \partial T / \partial r \\
& @ \quad r = \infty \\
& \quad T = T_\infty \quad Y_O = Y_{O_\infty} \quad Y_i = 0 \quad (i = F, CO_2, H_2O) \\
& \quad \partial \Phi / \partial r = - (1/T_\infty) * \partial T / \partial r
\end{aligned}$$

$$\begin{aligned}
& @ \quad \theta = \pi \\
& \quad T(r) = T_c + (r_c - r)/(r_c - 1) * (T_b - T_c) \quad \text{at } 1 < r < r_c \\
& \quad T(r) = T_c \quad \text{at } r_c < r < \infty \\
& \quad \partial Y_i / \partial \theta = 0 \quad (i = F, O_2, CO_2, H_2O) \\
& \quad \partial \Phi / \partial \theta = - (1/T_\infty) * \partial T / \partial \theta \\
& @ \quad \theta = 0 \\
& \quad \partial T / \partial \theta = \partial \Phi / \partial \theta = \partial Y_i / \partial \theta = 0 \quad (i = F, O_2, CO_2, H_2O)
\end{aligned}$$

This set of equations is solved numerically by a time-marching scheme started with prescribed initial profiles of temperature, velocity and species.

Figure 4(a) shows the temperature distribution in 0.23 mole fraction O_2 ambient. Only one-half of the picture is shown because of symmetry. The computed peak temperature is around 1710 K and a cool zone exists near the wick (or cold rod). Figure 4(b) shows the fuel-vapor mass-fraction contours. Some fuel vapor leaks out from the inside of the flame because of the quench layer near the wick. Similarly oxygen, shown in Figure 4(c), diffuses through this cool zone into the fuel-rich zone between the flame and the wick, thus creating a small partially premixed region. Figure 4(d) is a plot of the fuel vapor reaction(consumption) rate contours. These contours are the best indicator of blue visible flame in models with one-step kinetics. Grayson¹¹ used $w_F = 0.1 \text{ g/mm}^3 \text{ s}$ to represent the edge of the blue flame (minimum visible reaction rate) in solid-fuel flame-spread modeling, and we adopt the same criterion. Figure 4(d) clearly shows a quench zone near the wick.

Comparison between the computed flame shape and the experimental photographs shows good agreement. The numerical model produces a more hooked base than is present in the experiment. This is perhaps due to the finite thickness of the candle which the model treats as infinitely thin. The flame width, D , (outside edge of the flame, or $w_F = 0.1 \text{ g/mm}^3$) is 14 mm and height, H , is 12.5 mm which is very close to the quasi-steady experimental value (Figure 2). The computed flame dimension depends on the porous sphere diameter, in this case $R = 0.6 \text{ mm}$ which is close to radius of the small wick used in the experiment. The computed mass burning rate $m = 1.46 \times 10^{-4} \text{ g/s}$ is close to the lower end of the measured range. Note that the computed aspect ratio H/D is equal to 0.89. This falls in the range of experimentally observed H/D ratios.

Future modeling effort may include the study of flame extinction condition, near-limit oscillations, improvement of radiation treatment and the extension to include processes occurring inside the porous wick.

Conclusions and Discussion

The candle flames in the Mir tests had much longer lifetimes than those on USML-1. This is due to less resistance to oxygen transport through the candle box and a higher ambient oxygen concentration. The ambient oxygen mole fraction in the Shuttle tests was 0.217. In the Mir tests the range was from 22.5 to 24.9%. This difference alone would not however extend the lifetimes by a factor of 10 or more, as was observed. Thus, the predominant reason for the observed increase in flame lifetime for the Mir tests was the re-designed candle box.

Given a flame lifetime of up to 45 minutes, we believe that the gas-phase was quasi-steady, implying that the flame was steady over a time period much longer than any reasonable characteristic gas-phase transport time. Predictions from the numerical model suggest that the time to reach quasi-steady behavior for the gas-phase region inside the flame is only 10 seconds. This is consistent with drop tower and previous low gravity experiments where the flame quickly established a near-constant size.

Spontaneous oscillations are inherent to the near-extinction burning of these flames. The observed frequency was consistent with those seen before in low gravity, and are much less than observed in normal gravity^{8,9}. The apparent dependence on wick diameter, implying a dependence on flame size, suggests that flame radiative losses may contribute to the onset of oscillations, as hypothesized by Cheatham and Matalon^{3,4}.

The rapid melting of the wax is due to the conductive (and radiative) feedback to the solid wax. The liquid wax accumulates on the wick, rather than dripping as it does in normal gravity. When the wax collapses, the flame became blue as a result of reduced wax vapor supply to the flame. The result is a lower flame temperature than needed to

produce soot. The liquid flow visualization was fortuitous, and confirmed expectations that a significant flow persists throughout the flame lifetime. The source of the bubbles is likely the air captured in the wick matrix during fabrication of the candles. As the wax melted, the air bubbles were transported into the liquid, and served as flow tracers. Quite unexpected, however, was the aerosol flow that began upon ignition.

Only a few experiments were performed with two candles, so we do not report detailed results in this paper. One finding, however, was that, unlike USML-1, both candles could be lit in close proximity to each other, because they were ignited simultaneously. This verified the hypothesis that the procedure of sequential ignition was the cause of the failure to ignite both candles in the earlier tests.

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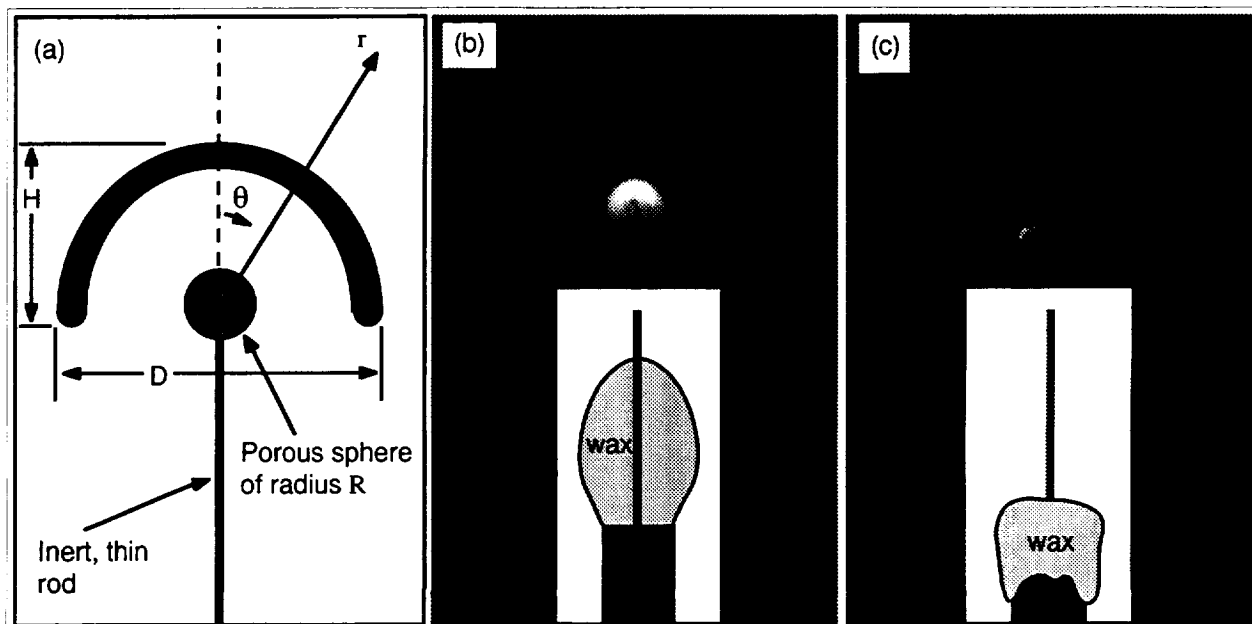


Figure 1. (a) Schematic of a microgravity candle flame with relevant dimensions and coordinate system for numerical model; (b) Candle flame before wax collapse and; (d) Candle flame after wax collapse.

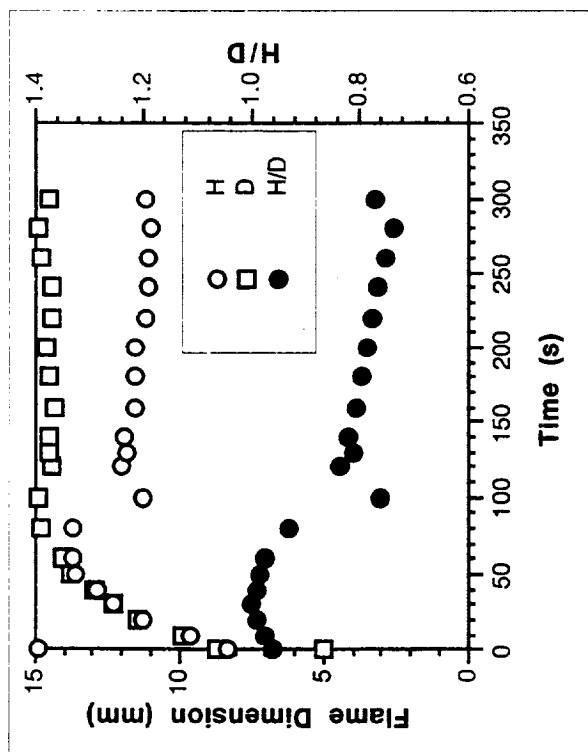


Figure 2. Candle flame height, H , and diameter, D as a function of time for a candle with a small wick.

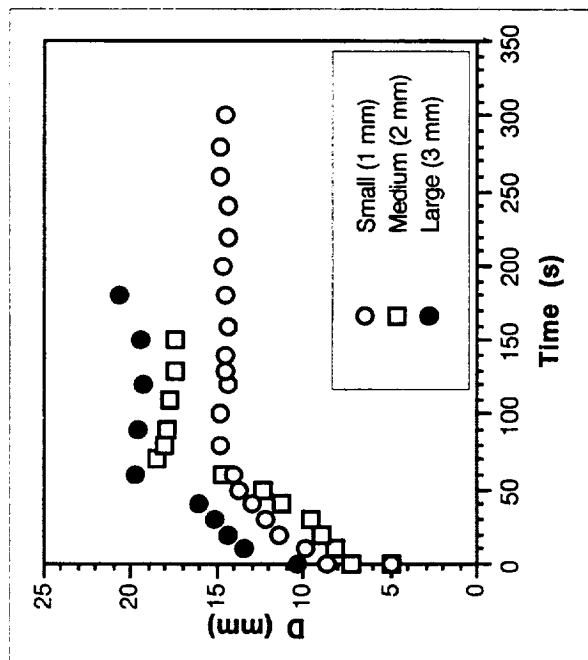


Figure 3. Flame diameter as a function of time for three different wick diameters.

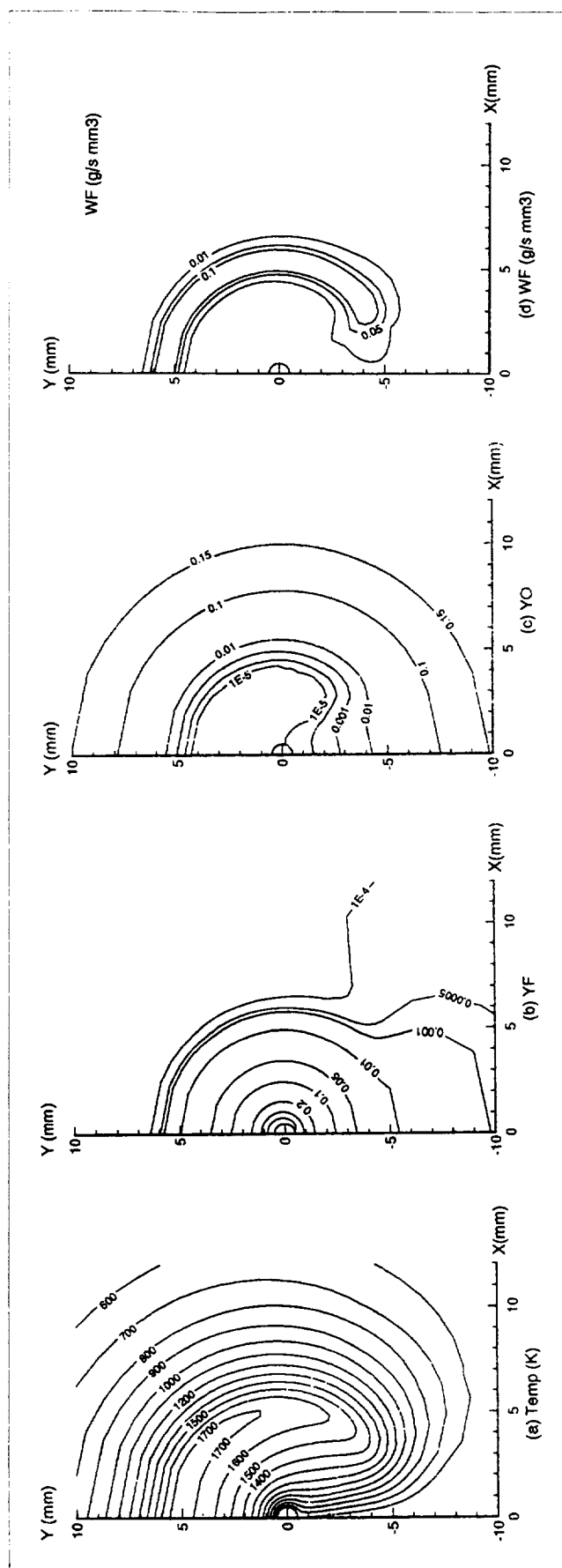


Figure 4. Numerical modeling results for a sphere diameter of 1.2 mm in a 1 atm, 0.23 oxygen mole fraction ambient.